Fluctuations of Mid-to-High Frequency Acoustic Waves in Shallow Water

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LONG-TERM GOALS

The long-term goal of this project is to obtain quantitative understanding of the physics governing broadband frequency (50 Hz to 50 kHz) acoustic signal propagation, reflection, refraction and scattering in shallow water and coastal regions in the presence of temporal and spatial ocean variability.

OBJECTIVES

Scientific objective of this research is to understand acoustic wave propagation in a dynamic environment in two different frequency bands: (a) Low frequency band (50 Hz to 500 Hz). The subject of interest in this band is to assess the effect of environment anisotropy on acoustic wave propagation, with an emphasis on the separation of different effects due to horizontal refraction and mode coupling from adiabatic regimes, (b) Mid-to-high frequency band (500 Hz to 25 kHz). The subject of interest in this band is to assess the effects of the water column and the sea surface variability on acoustic wave propagation for underwater acoustic communications and tomography applications.

APPROACH

Combined experimental, theoretical, and modeling efforts are devoted to gain understanding of broadband acoustic wave propagation in shallow water. We aim to learn in detail about the channel impulse response (CIR) function with respect to environmental variations. Studies carried out in the low frequency band have been focused on the analysis of archival data as well as recently obtained field data during the SW06 experiment [1]. We have investigated the structure of the continuous and trapped horizontal (x-y plane) modes, which are created in between the internal wave fronts. Both ray and PE representations have been used.

The mid-to-high frequency band part of our research is based on the experimental data collected during HFA97 in Delaware Bay [2], KauaiEx 2003 [3], and MakaiEx 2005. The effects of the sea surface and the water column variability on acoustic wave propagation have been studied for two types of applications: underwater acoustic communications and high frequency current tomography.

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14. ABSTRACT

The long-term goal of this project is to obtain quantitative understanding of the physics governing broadband frequency (50 Hz to 50 kHz) acoustic signal propagation, reflection, refraction and scattering in shallow water and coastal regions in the presence of temporal and spatial ocean variability.

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WORK COMPLETED

Progress has been made in understanding the three-dimensional (3-D) effect of low frequency propagation in shallow water in the presence of internal waves [5-8]. The effects due to the horizontal refraction are separated from those due to mode coupling and adiabatic conditions. Based on these results, a hypothesis is developed for further investigation and the SW06 experiment has been conducted to test the theory. In the high frequency band research, we have been analyzing the KauaiEx 2003 and MakaiEx 2005 data as well as the HFA97 data for current tomography studies. We have developed new receivers for underwater acoustic communications. Furthermore, we have upgraded our data acquisition system for future experimental observations.

RESULTS

In the following sections, results for both low and high frequency bands are presented. These highlights are based on papers and reports resulting from our existing research grants [1-9].

A. Environmental Effects on High Frequency Acoustic Wave Propagation

KauaiEx 2003 [3, 4] was conducted to study ocean variability effects on high frequency acoustic wave propagation. Through experimental research and data analysis, it is shown that high frequency acoustic propagation is affected by the temporal and spatial changes in the water column and the sea surface. It is also shown that the ocean variability impacts arrival rays differently depending on their travel paths.

For example, acoustic measurements on the Marine Physical Laboratory (MPL) array during KauaiEx 2003 show prominent depth and range dependent effects on high frequency acoustic wave propagation. During KauaiEx, the MPL array had a large aperture in the water column, from 20 m to 95 m depth at 3 km range. Most acoustic arrivals at the top hydrophone have surface interactions. In contrast, refracted and bottom-reflected arrivals are populated on the bottom hydrophone. Such depth dependent ray structure is clearly shown by the channel intensity impulse response (CIIR) functions across the MPL array. Fig. 1 shows the variability of acoustic signals received on the MPL array, along with the measured temperature profile and surface wave spectrum, from 04:00 GMT on July 2 to 07:00 GMT on July 3, 2003. Figs. 1(c) and (d) show the CIIR functions on MPL array for the top (#1) and bottom (#16) hydrophones, respectively. The correlation between the surface reflected arrival group (marked with 3 in Fig. 1(c) and (d)) and the measured surface waves is clearly shown. From 04:00 to 16:00, the sea surface is calm due to low winds and the surface reflected rays on both hydrophones are higher in energy than at a later time which starts at about 21:00 when the sea surface becomes rough. A strong downward refracting sound speed profile from 17:00 to 20:00, corresponding to the stratified water column shown in Fig. 1(a), steers the rays toward the bottom so that strong refracted-bottom-reflected ray paths (marked with 1 in Fig. 1(d)) arrive on the bottom hydrophone as shown in Fig. 1(d).

The depth and range dependent effects on high frequency acoustic wave propagation have impact on the performance of coherent underwater acoustic communications. To show such effects on simultaneous communications in the upper and the lower water column, the top 8 hydrophones of the MPL array (MPL-TOP) or the bottom 4 hydrophones of the MPL array (MPL-BTM) are considered as sub-arrays. Fig. 2 shows the output SNR ρ_{out} on the three arrays, the APL, MPL-TOP, and MPL-BTM arrays, for 34 hours.
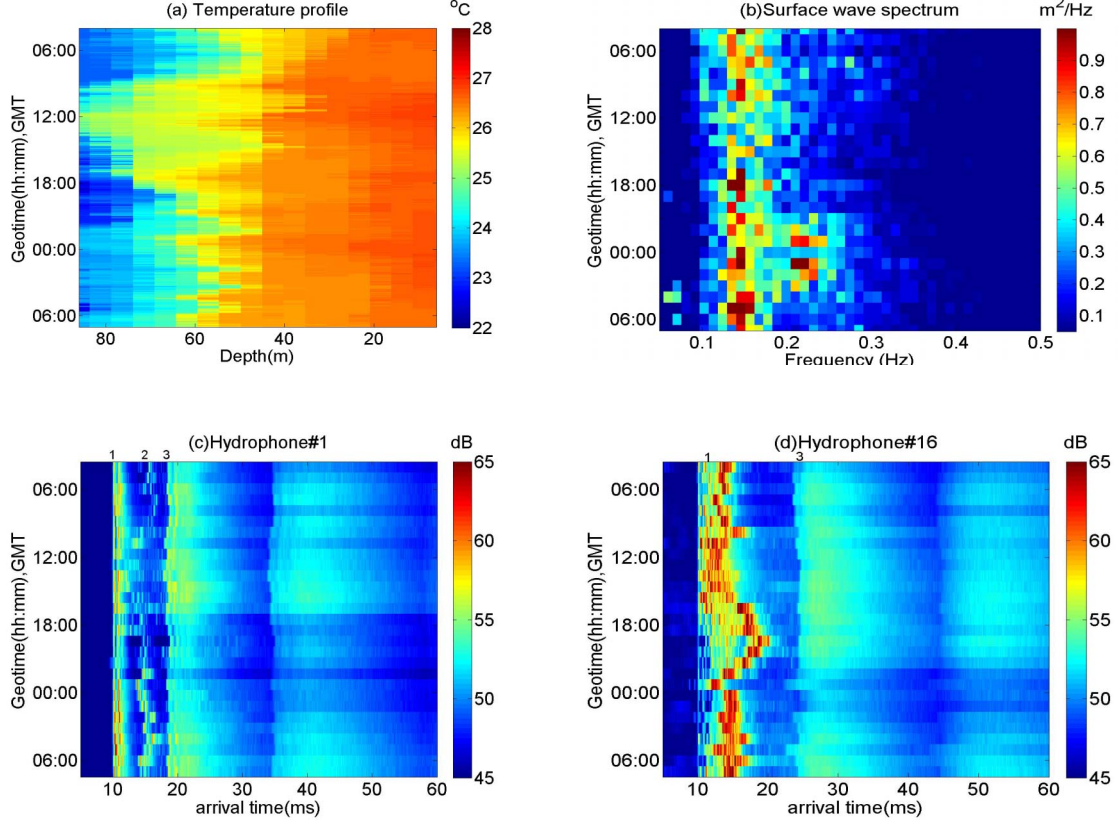
Figure 1: (a) Temperature profile during 04:00 on July 2 to 07:00 on July 3, 2003. (b) Surface wave spectrum measurement. The CIIR function obtained from the recorded LFM signal versus geotime from 04:00 on July 2 to 07:00 on July 3, 2003 (c) on the top hydrophone near the sea surface at 20 m and (d) on the bottom hydrophone near the sea floor at 95 m from the surface. In subplots (c) and (d), the signal group marked with 1 contains mainly acoustic arrivals without surface interactions; the signal groups marked with 2 and 3 contain surface interacting arrivals.

During the 34 hour MPL array recording period, the environment parameters underwent significant changes as indicated by the measured sea surface wave spectrum in Fig. 2(a) and the water temperature in Fig. 2(b) along the propagation track. Due to propagation variability, the performance of the receiver also experiences prominent changes. On the MPL-BTM array, the output SNR increases about 4 dB when the well mixed water column with relatively calm sea surface condition (around 12:00 on July 2, 2003) changes into a layered water column with rougher sea surface condition (around 22:00 on July 02, 2003). In contrast, on the MPL-TOP array, the output SNR experiences a much smaller increase when the environment experienced similar changes. Compared with the MPL-TOP array, or even the APL array, the same receiver with the bottom 4 elements usually has superior performance to that with the 8 elements in the upper water column, where the received acoustic field involves significant interaction with the dynamic ocean surface.

A separate report has more results on underwater acoustic communications receiver design and the ocean variability effects on the performance of coherent underwater acoustic communications.

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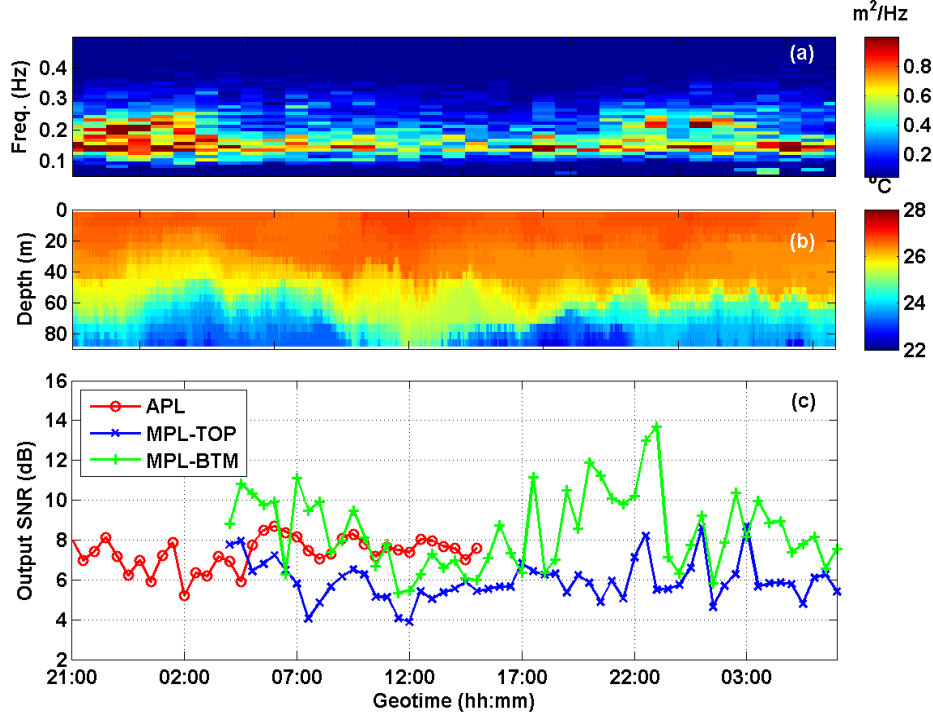
Figure 2: The output SNR of the time reversal receiver during KauaiEx over an extended period (34 hours) from 21:00 GMT on July 1 to 07:00 GMT on July 3, 2003. Note that the output SNR on the MPL-BTM array when the water column was well mixed with a relatively calm sea surface condition (around 12:00) on July 2 is about 4 dB higher than that when the water column was layered with a rougher sea surface condition (around 22:00 on July 02, 2003).

B. High Frequency Current Tomography in Shallow Water Regions

Acoustic tomography in shallow water is complicated due to interactions of acoustic waves with sea surface and bottom. Recently a number of experiments have been conducted in coastal areas and the tomography data are assimilated into ocean models to estimate the current structures [10]. Here we assess the acoustic center frequency effects and present a case study in which current tomography was achieved for two different acoustic center frequencies of 4 kHz and 12 kHz using the direct and multi-bounced paths in different sea surface conditions.

Data from the HFA97 experiment conducted from September 23 to 29, 1997 have been analyzed for the study. The experimental setup included three stable tripods, each having an acoustic source and three receiving hydrophones. On each tripod, the source was located 3.125 m above the sea floor and the hydrophones were located at 0.33, 1.33, and 2.18 m above the sea floor respectively. The average water depth was 15 m and the distance between the two tripods was 389 m. The sources transmitted broad-band chirp signals over the frequency range of 1-25 kHz. A reciprocal acoustic test was conducted using two pairs of source/receiver arrays mounted on tripods. Current profile was measured at one point between the two acoustic source/receiver pairs using ADCP. Given the measured travel time of reciprocal transmission and the distance between a source/receiver pair, the current speed can be estimated.
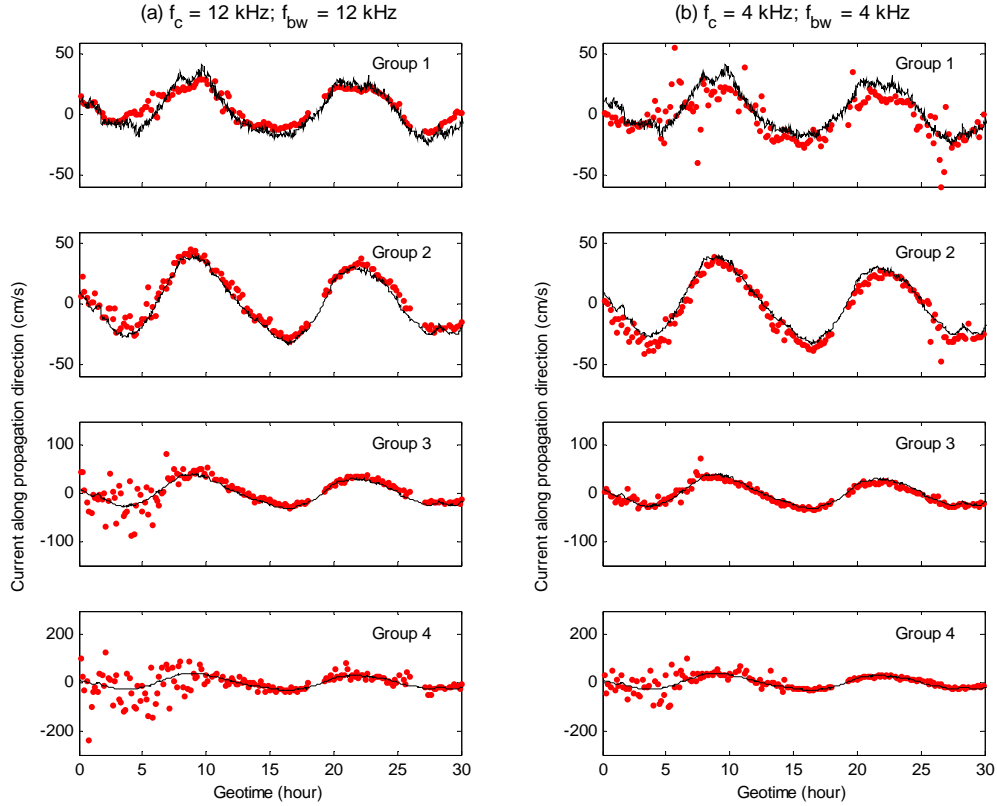
Figure 3: Comparison between the ADCP measured current speed projected onto the path between the source and the receiver (solid line) and the inverted acoustic current speed for 4 arrival groups during the 30 hour observation starting at 05:00:00 on 24 September 1997 (red dots). Group 1 represents the direct and bottom-bounced paths, Group 2 represents rays having one surface interaction, Group 3 represents rays having two surface interactions, and Group 4 represents rays having three surface interactions. (a) The acoustic center frequency and bandwidth are both 12 kHz. (b) The acoustic center frequency and bandwidth are both 4 kHz. For all groups, the inverted acoustic current speed compares well with ADCP data for calm sea states (after hour 10).

The accuracy of the current tomography depends on the reciprocal transmission arrival time measurements. This arrival time is identified by the arrival peaks [2] using a space-time beamforming technique. The current speed is calculated using the measured first arrival time in each group.

In Fig. 3 the current speed estimation for 30 hours starting at 5:00 on September 24, 1997 is compared with the ADCP current measurements. The wind speed varied between 2 m/s to 13 m/s in the first 10 hours and was low (less than 2 m/s) after hour 10. For Group 1 (direct and bottom-bounced paths), the estimated current speed was compared with the near bottom ADCP measurements projected onto the path between the source and the receiver, while for later groups (sea surface-bounced paths) it was compared with the depth-averaged ADCP measurements also projected onto the path between the source and the receiver. Figs. 3(a) and 3(b) are for center frequency 12 kHz with a bandwidth of 12 kHz and center frequency 4 kHz with a bandwidth of 4 kHz, respectively. The current speed can be estimated accurately for calm sea states (after hour 10) and the accuracy decreases when the sea surface roughness increases. The differences in amplitude are partly due to the fact that the acoustic

measurements give an average between the source and the receiver, while the ADCP is a point measurement. With regard to the acoustic center frequency, it is noticed that the accuracy of the first arrival group is higher with higher center frequency and bandwidth, while the later arrivals provide better estimations at a lower center frequency and bandwidth.

C. Low Frequency Acoustic Wave Propagation in the Presence of Shallow Water Internal Waves

We have recently shown the contribution of the internal waves in sound intensity fluctuations in relation to the index of refraction [5-7]. Sound intensity fluctuates due to horizontal refraction for a certain range of angles between the acoustic track and the direction of internal waves. Other fluctuations are due to mode coupling [6], which is enhanced when internal solitons (IS) propagate approximately along the acoustic track. For a moving IS relative to a fixed source-receiver position this can be perceived as temporal fluctuations with typical frequencies of about 1 - 10 cycles per hour (cph).

To model this, we assume a perturbation of sound field due to a localized, intense IS moving with a constant velocity v and an angle α between the direction of the acoustic track and the wave front of the IS. At a geophysical time T (referred to as "slow" time), this perturbation in the waveguide occupies a region at range $R < r < R + \Delta R$, where $R = vT$, and ΔR is the "length" of the soliton. As a result we have a small addition to the sound speed profile $\delta c(r,z,T)$ in the region which depends on the "slow" time T [8]. When acoustic interaction with this moving soliton takes place in the region $R < r < R + \Delta R$, the modal decomposition can be written using S-matrix formulation [8], so that in the range $r > R + \Delta R$ the sound field pressure is

$$P_\omega(r,z;R) = iS(\omega)\sum_{m,l}\frac{\psi_l(z_s)\psi_m(z)}{\sqrt{8\pi i q_m r}}S_{ml}(R+\Delta R,\omega)\exp\left[i\left(q_m(r-R)+q_l R\right)\right]$$

(1)

where $\psi_l(z)$ is the waveguide mode with eigenvalue q_l. The S-matrix satisfies the equation with "initial" condition $\dfrac{d\mathbf{S}}{dr} = \mathbf{WS}$, with $\mathbf{S}(R) = \mathbf{I}$ and $\mathbf{I}$ is the unit matrix. The coefficient of interaction between modes in simple perturbation theory is

$$W_{ml}(r) = i\frac{k^2\exp[i(q_l-q_m)r]}{\sqrt{q_m q_l}}\int_0^H\frac{\delta c(r,z)}{c}\psi_m(z)\psi_l(z)dz.$$

(2)

Because the "slow" time $T = R/v$, sound pressure at the receiver depends on time T. Assuming that the strongest coupling interaction is between adjacent modes, we can write a form for the normalized amplitude of mode m created from mode $m+1$:

$$A_{m,m+1} = \left|\frac{\psi_{m+1}(z_s)\psi_m(z)}{\sqrt{8\pi i q_m}}S_{m,m+1}\right|.$$

(3)

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This quantity depends on frequency, and for each pair of coupling modes, the coefficients in Eq. (3) have their own "optimal" frequency, denoted as $\omega_{opt}^m = \omega_{opt}^{m,m+1} \sim \omega_{opt}^{m+1,m}$, where the value of Eq. (3) has a maximum. This maximum corresponds to the situation where the two coupling modes have turning point positions within (or close to) thermocline layer. In this case, pairs of coupling modes have approximately the same scale of interference beating $D_{opt} = 2\pi / \left|\Delta q_{m+1,m}\right|_{\omega=\omega_{opt}^m} \approx$ constant.

Amplitude of sound field fluctuations
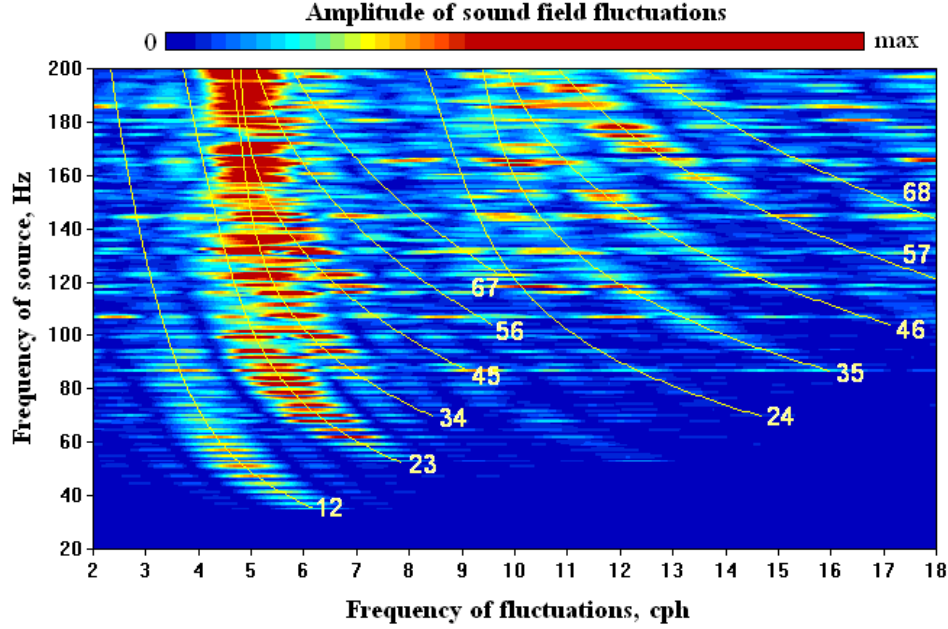
Figure 4: A Frequency-frequency (fF) diagram for the SWARM95 in color gradation: Spectral intensity G of received signal as a function of frequency. The thin yellow lines are the curves where $v\left|\Delta q_{m,m+1}\right| = $ constant.

In Fig. 4, we show the result of a calculation of the spectrum of intensity fluctuations $G(\omega,\Omega) = \int_0^{\Delta T} \delta I_\omega(T) e^{i\Omega T} dT$, where $\delta I_\omega(T)$ is the intensity perturbation, for different sound frequency using a color scale. For this modeling, we take waveguide parameters corresponding to the SWARM95 experiment [9]. We call this picture a "frequency-frequency (fF)-diagram". The maxima in these spectra are found on the curves $v\left|\Delta q_{m,m+1}\right| = $ constant, shown by thin yellow lines. Every slice of these curves by a horizontal straight line gives the spectrum of the fluctuations for a given sound frequency. We see that in these spectra there are many maxima, with the most significant one corresponding approximately to the fluctuation frequency $\Omega_{opt} = v\left|\Delta q_{m,m+1}\right|_{\omega=\omega_{opt}^m}$. However, for different sound frequencies, this predominating frequency of oscillation is provided by different pairs of modes. For

example, in the region of $\omega \sim \omega_{opt}^1 \sim 50$ Hz, the value of $\Omega_{opt} \sim \Omega_{12}$, whereas in the region of $\omega \sim \omega_{opt}^2 \sim 100$ Hz, the value of $\Omega_{opt} \sim \Omega_{23}$, etc.

The value of the dominant fluctuation frequency is $\Omega_{opt} \sim 13 \cdot 10^{-4}$ Hz (i.e. $\sim$ 5-6 cph). Existence of this dominant frequency of intensity fluctuations is a result of the previously mentioned constant length scale for the interference beating of pairs of modes at "optimal" frequencies. Rough ray theory estimation for the cycle distance of a ray tangent to thermocline layer gives $D_{opt} \sim$ 700-800 m, which corresponds to the above mentioned value of frequency $\sim$ 5 cph. We also note that the estimated velocity of soliton, $v_s \sim$ 0.7 m/s, is in accordance with previous data [5, 6].

The aforementioned model which was developed last year is currently being used to interpret the SWARM95 data [9]. Further extension of this analysis will be done for the SW06 experiment [1].

D. Instrumentation

Because of the high data throughput and long endurance requirement, data acquisition systems for high frequency acoustics are not commercially available. We have designed and fabricated a stable platform composed of a sound source and eight hydrophones placed on a bottom mounted tripod. We have expanded our design to be able to conduct autonomous reciprocal transmissions in shallow water. In a separate DURIP grant during FY06-07, we have initiated fabrication of this new generation data acquisition system for our future field experiments [11].

IMPACT/APPLICATIONS

The low frequency part of our research benefits the science of understanding sound propagation in complex shallow water regions. We have developed a theory to explain the fluctuations of the arrival time and the intensity due to mode coupling caused by internal solitons moving approximately along the acoustic track. The high frequency part of our research has impacts on the development of new underwater communications systems with more efficient decoding capabilities. The correlation of the time reversal receiver performance with the characteristics of the surrounding ocean environment presents new insights into operational effectiveness of underwater acoustic modems. The study in current tomography has shown the feasibility and the accuracy of high frequency current tomography in shallow water using the direct and multi-bounced acoustic ray paths for different sea surface conditions.

RELATED PROJECTS

In the low frequency band research, we have been working with Drs. J. Lynch at Woods Hole Oceanographic Institute (WHOI), and B. Katsnelson from University of Voronezh, Russia. For the research work in the high frequency band, we are collaborating with colleagues from Scripps Oceanographic Institution (Drs. W. Hodgkiss and W. Kuperman), Applied Physics Laboratory-University of Washington (Dr. D. Rouseff), and Heat, Light, and Sound Research Inc. (Dr. M. Porter).

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